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Bulge evolution in face-on spirals and low surface brightness galaxies

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ABSTRACT

It is an observational fact that bulges of spiral galaxies contain a high fraction of old and metal-rich stars. Following this observational fact, we have investigated colors of 21 bulges hosted by a selected sample of high surface brightness spirals and low surface brightness galaxies observed in B and R optical bands and in J and K_s near-IR bands. Using structural parameters derived from these observations we obtain evidence that bulges could be formed by pure disk evolution (secular evolution), in agreement with the suggestion by some authors. The color profiles, especially the near-IR ones show null or almost null color gradients, supporting the hypothesis that the disk stellar populations are similar to those present in the bulge, and/or some bulges can be understood as disks with enhanced stellar density (or pseudobulges). In the optical, half of the galaxies present an inverse color gradient, giving additional evidence in favor of secular evolution for the sample investigated. The comparison of the observed colors

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with those obtained from spectrophotometric models of galaxy evolution suggests that bulges of the selected sample have solar and subsolar metallicity, and are independent of the current stellar formation rate. Also, we obtain evidence suggesting that galaxies hosting small bulges tend to be systematically metal poor compared to those with larger bulges. These results are being checked more carefully with high S/N spectroscopy.

Subject headings: galaxies: bulges — galaxies: evolution — galaxies: fundamental parameters — galaxies: irregular — galaxies: peculiar — galaxies: photometry — galaxies: stellar content — galaxies: structure

1. Introduction

Low surface brightness (LSB) galaxies have become important members of our extragalactic zoo. Since Disney (1976) showed that the central surface brightness limit of $\mu_0(B) = 21.65$ mag arcsec^{-2} in spirals claimed by Freeman (1970) was just a selection effect due to the narrow surface brightness sensitivity of photographic plates, the discovery of LSB galaxies in huge numbers in the universe gave rise to a new field of study in astronomy: the low surface brightness universe. Since then, a wealth of observational data (Longmore et al. 1982; Bothun et al. 1985; Bothun, Impey & Malin 1991; McGaugh, Schombert & Bothun 1995; O'Neil, Bothun & Schombert 2000) and theoretical work (McLeod & Rieke 1995; Sprayberry et al. 1997; de Blok & McGaugh 1997; Dalcanton, Spergel & Summers 1997a; McGaugh & de Blok 1998a; Chuiueh & Tseng 2000; Bell 2002; McGaugh, Barker & de Blok 2003; Swaters et al. 2003) has been invested not only to describe the most relevant features of these galaxies, but also to analyze whether these features are consistent with models of galaxy formation and evolution. In the observational front, LSB galaxies have been investigated in the optical (Dalcanton et al. 1997b; Bergvall et al. 1999; Burkholder, Impey & Sprayberry 2001) in the near-IR (Romanishin et al. 1982; Bergvall et al. 1999; Bell et al. 2000; Galaz et al. 2002; Monnier-Ragaigne et al. 2003), in radio wavelengths, including studies of the HI distribution (Hoeppe et al. 1994; Longmore et al. 1982; de Blok, McGaugh & van der Hulst 1996; Matthews, van Driel & Monnier-Ragaigne 2001), detected and mapped in CO (O'Neil, Hofner & Schinnerer 2000; Matthews & Gao 2001), and also studied spectroscopically (Impey, Burkholder & Sprayberry 2001; Bergmann, Jorgensen & Hill 2003), including the analysis of rotation curves (McGaugh, Rubin & de Blok 2001; de Blok, McGaugh, & Rubin 2001) and the Tully-Fisher relation (Sprayberry et al. 1995; Chung et al. 2002).

These references strongly indicate that LSB galaxies are unevolved systems with low

stellar formation rate (SFR), low metallicity, small stellar density, relatively high gas fractions and, from dynamical information, large amounts of dark matter. However, several challenging questions still remain. First, in spite of the evidence indicating that LSB galaxies are young when compared with spectrophotometric models, the spread in color is wide, implying that they have probably gone through diverse evolutionary paths. Moreover, the fact that only small amounts of blue stars are needed to make bluer the integrated colors, due to the small stellar density, makes some LSBs appear spuriously younger than they really are. Or, equivalently, small changes in the SFR make galaxies look much younger what they actually are. Second, while emission line analysis of a few spectra of LSB galaxies have revealed the metallicity of the current *gas phase* (Impey, Burkholder & Sprayberry 2001; Bergmann, Jorgensen & Hill 2003), the metallicity of the *underlying stellar population*, as measured for example using absorption lines, has not been possible to be determined, except in some few cases (Bergmann, Jorgensen & Hill 2003). Third, the total stellar mass of LSB galaxies is still poorly estimated, mostly due to the large uncertainties in the stellar mass-to-light ratios at optical wavelengths. Only recently, less scattered M/L ratios have been derived using near-IR bands, where the extinction due to dust has a smaller effect than in optical wavelengths (Galaz et al. 2002). Finally, recent modeling of LSB galaxies predict that, under the assumption that blue LSB galaxies are currently undergoing a period of enhanced stellar formation, *there should exist* a population of *red*, non bursting, quiescent LSB galaxies (Gerritsen & de Blok 1999; O'Neil, Bothun & Schombert 2000).

In the context of the old stellar content of disk and LSB galaxies, the bulge or nuclear component plays a fundamental role as it also affect any analysis where rotation curves are studied (Valenzuela & Klypin 2003; Rhee, Klypin & Valenzuela 2003). Although by the proper Hubble morphological definition late type spirals tend to be bulgeless, recent studies with the HST have shown that many late type, face-on spirals apparently bulgeless, have in fact small, tiny bulge (Böker, Stanek & van der Marel 2003) missed by studies where the spatial resolution was not good enough to resolve such small bulges. One of the recurrent questions is whether many of these bulges hosted by LSB galaxies or disks with low stellar density, are in fact high surface brightness bulges embedded in LSB disks. In such a case the bulge could evolve independently with respect to the disk, and one should expect that bulges in LSB disks present more or less the same metallicity than bulges of HSB galaxies.

On the other hand, the secular evolution of galaxies, i.e. the idea that the bulge is formed from disk evolution, allowing the direct formation of bulges from disks in isolated galaxies, implies that the stellar population of disks are similar to those in bulges. For example, one can expect that color gradients are less violent, or even inverse (red to blue, from the center to the outskirt of the galaxy). Also, one can expect that light profiles are fitted only by a combination of exponential profiles, instead of the classic de Vaucouleurs +

exponential profile (Courteau, de Jong & Broeils 1996; Kormendy & Fisher 2005). In this sense, secular evolution could produce what is called a pseudobulge, structurally similar to a bulge, although more comparable to disk when its stellar population is analyzed and/or its light and color profile is studied.

In this paper we explore possible evolutionary scenarios for a set of selected face-on spirals and LSB galaxies, using a combination of optical and near-IR colors. In particular, we investigate the observables and structural parameters in scope of the secular disk to bulge evolution, as stated for example in Courteau, de Jong & Broeils (1996). Most galaxies investigated here are face-on *nucleated* LSB galaxies; all of them are part of the catalogue published by Impey et al. (1996). We also investigate the stellar content of the bulges. The goal of this paper is to determine what ranges of metallicities and ages are consistent with bulge and disk formation scenarios, by comparing observed B, R, J and K_s magnitudes and colors with spectrophotometric models of galaxy evolution. We have selected a subsample with prominent bulges, for which we have carefully studied their structural parameters (bulge and disk scale lengths, surface brightnesses). For this subsample, we present radial brightness profiles and color gradients, both in optical and near-IR bands. Secular evolution is analyzed in scope of these results. In §2 the sample selection is presented. Observations and data reduction are described in §3. In §4 we present results and a basic analysis. In §5 we present a discussion in scope of the bulge formation in HSB and LSB galaxies. We conclude in §6.

2. Sample selection and previous observations

Galaxies presented here were originally selected from the catalogue of Impey et al. (1996). The sample includes galaxies with $21.0 \leq \mu_0(B) \leq 23.5$ mag arcsec^{-2}, with HI masses such that $7.49 < \log(M_{HI}/M_{\odot}) < 10.69$, and with DEC < 5 deg, covering all RA. Our sample includes not only LSB galaxies, but HSB galaxies as well. This allows to generate a continuous sequence for properties derived for LSB galaxies and HSB galaxies, like colors, structural parameters, etc. (Galaz et al. 2002). The total original catalogue amounts 107 galaxies which satisfy these constraints. 77 galaxies were already observed in the near-IR at Las Campanas Observatory between 1999 and 2000. Observations and reductions for this data set are described in Galaz et al. (2002). From these 77 galaxies with near-IR photometry, 55 galaxies were observed during photometric nights in B (Johnson) and R (Cousins). In this paper, we focus our attention on a subsample of 21 face-on nucleated galaxies out of these 55 spirals. In order to prevent undesirable strong internal reddening due to the effect of inclination, we have selected only face-on nucleated spirals (defined following Hubble morphological classification scheme) for which we were interested to reach

faint isophotes to $\mu_0(B) \sim 25.0$ mag arcsec^{-2}. The face-on criteria is defined such that galaxies are spirals with inclinations smaller than 20 deg[5]. In fact, the combined optical and near-IR imaging (Galaz et al. 2002) allow us to select galaxies with prominent bulges. The 21 spirals exhibit central surface brightnesses between 21 and 23 mag arcsec^{-2}, in the B band, allowing to reach the desirable central surface brightness limit. Figure 1 shows an optical mosaic of the 21 galaxies selected for the main part of this study. Note that all galaxies present bulges. Also note that 6 galaxies are barred.

3. Observations and data reduction

3.1. Observations

Optical observations were strictly performed during photometric nights in three runs at Las Campanas Observatory, using the 2.5m du Pont telescope. The first two runs took place in April and August 2000, and the third one was in April 2002. In all of them we used the same detector: a 2048×2048 Tek#5 CCD of 0.259 arcsec/pixel scale and 8.8 arcmin FOV. The CCD present low read out noise (4.2 e$^-$) at a gain of 3.0 e$^-$/ADU. Typical exposures were between 800 and 1200 secs, splitted in two exposures per galaxy per filter. Typical seeing was around 0.9 and 1.2 arcsec in the B band, and 0.8 and 1.0 arcsec in the R band.

3.2. Reductions

With the purpose of obtaining an acceptable accurate photometry for our sample, it is important to reduce very carefully our set of images. Special attention was taken in the flat-fielding process and fringing corrections, particularly in the R band. In fact, low (flat) and high (fringes) frequency spatial variations can introduce a spurious systematic signal over the CCD that affects the surface brightness estimate of our galaxies. In order to reduce as possible these kind of effects, we build-up a super flat for each filter from observations, especially in R, where fringes dominate the spatial signal variations at high frequencies. A Fourier transform of the images allows to detect the most common spatial patterns. Also, and before flat-fielding, images were cleaned-up from cosmic rays, bad pixels and dead columns.

[5]Note that galaxy 515 is probably at the limit of this criterion, having an inclination angle of $i \sim 45$ deg. This turns its disk surface brightness about $2.5 \log[\cos(i)] = 0.37$ magnitudes fainter, at most.

Images were finally aligned[6] and averaged.

3.3. Photometric calibrations

After removing instrumental effects and pixel to pixel variations, images were photometrically calibrated. The usual method based on observation of Landolt standards (Landolt 1992) was used. We observed no less than 15 standards per night, allowing to derive accurate zero points and color terms for our transformation equations

$$B = m_B + Z_B + k_B * X_B + C_B * (m_B - m_R) \quad (1)$$

$$R = m_R + Z_R + k_R * X_R + C_R * (m_B - m_R), \quad (2)$$

where B and R are the calibrated magnitudes in the standard system; m_B and m_R are the instrumental magnitudes; Z_B and Z_R are the photometric zero points; k_B and k_R are the atmospheric extinction coefficients; X_B and X_R are the measured airmasses at the moment of the observation; and C_B and C_R are the first order color terms. All photometric reductions were performed with the IRAF PHOTCAL package.

Solving the two above equations independently for each night it is possible to determine the photometric quality of each night. The corresponding coefficients for each run are presented in Table 1. Errors of aperture photometry were computed using the standard rules of error propagation from original measured fluxes, taking into account the S/N ratio of the different stars and galaxies and also the detector features (read out noise and gain). In the error propagation we also take into account the effect of the various steps involved within the image reduction process (bias subtraction, flat field division, summing, etc...). The calibration for the corresponding J and K_s magnitude for each galaxy was already presented in Galaz et al. (2002).

Table 2 present B and R magnitudes for all spirals in the sample (from which a subsample of 21 face-on nucleated galaxies is taken, denoted as bold-face identifications). Magnitudes are calculated for the inner 2 kpc diameter, which is estimated using the radial velocity of each galaxy and the diameter angular relation with a Hubble constant H_0 of 75 km sec^{-1} Mpc^{-1}. Considering the typical size of the galaxies (see next section), we estimate that inside the inner 2 kpc radius we are including the typical bulge population. Along with the atmospheric extinction correction, we have applied to all images Galactic extinction corrections using the maps of Schlegel, Finkbeiner & Davis (1998).

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[6]During observation for each galaxy, telescope was shifted 3 arcsec ($\sim$ 10 pixels) between consecutive exposures to allow for photons of the same source to fall into different pixels.

3.4. Computing light profiles, color profiles and structural parameters

Structural parameters are consistently computed using the light profiles in the four bands B, R, J and K_s. These are derived using ELLIPSE (IRAF), which provide azimuthally averaged isophotes for each galaxy. From these values one can derive fitting parameters for both the bulge and disk components simultaneously (Beijersbergen, de Blok & van der Hulst 1999). From the isophote level we derive exponential profiles of the form

$$\Sigma(r) = \Sigma(0)\exp^{-(r/h)}, \tag{3}$$

where the structural parameters defining these profiles are $\Sigma(r=0)$, the surface brightness at $r=0$, in $L_\odot$ pc^{-2}; and h, the scale length of the bulge or disk, i.e., the radius at which we have $1/e$ times the central intensity. Transforming equation 3 to a logarithmic scale we have

$$\mu(r) = \mu_0 + 1.086(r/h), \tag{4}$$

where μ_0 is the central surface brightness in mag arcsec^{-2} for the disk, and r is the radial distance to the azimuthally averaged isophote. For the bulge component it is also common to use the $r^{1/4}$ profile law in the form

$$\mu(r) = \mu_e + 8.325\left[(r/r_e)^{1/4} - 1\right], \tag{5}$$

to fit the bulges of all kind of spiral galaxies (as they were similar to elliptical galaxy profiles), where μ_e is the surface brightness at r_e, the so-called effective radius containing half of the galaxian light. In fact, we do know that the exponent of the fit is correlated with the morphological type: light profiles of ellipticals and S0s follow the $r^{1/4}$ law (de Vaucouleurs 1948), and bulges of Sa and Sb fit better to $r^{1/2}$ profiles (Beijersbergen, de Blok & van der Hulst 1999).

We use the task NFIT1D in STSDAS/IRAF to fit two exponential (and $r^{1/4}$) profiles for the whole light curve, using a χ^2 minimization algorithm. Light profiles errors are related to the corresponding errors in the fitting parameters. These errors are derived from usual χ^2 minimization. In turn, each isophote has an associated error given by the ratio between the root-mean-square scatter around the isophotal intensity and the square root of the total pixels included in the isophote.

Table 3 shows optical structural parameters measured for the sample of 21 spirals. Table 4 shows the corresponding parameters measured from the near-IR brightness profiles. Parameters include central surface brightnesses and scale lengths for both the bulge and the disk in the four bands. Note that 38% of our sample is composed by bonna fide LSB spirals (fainter than 22.0 mag arcsec^{-2}), and the rest are in fact HSB spirals. This is useful to

clearly determine what properties in spirals suffer a continuous transition to the LSB regime and which do not. In particular, we are interested on colors and light profiles for our sample, since its behavior is one of the diagnosis for a bulge/disk evolution (see §5).

In this work, all disks are fitted better by an exponential profile of the form given by equation 3, or equivalently by its logarithmic version given by equation 4, from where the central surface brightness of the disk is computed. For bulges, the usual method is to use a $r^{1/4}$ profile (or de Vaucouleurs profile). However, we shall demonstrate that most of our galaxies are better fitted by a combination of *two* exponentials: one for the disk and one for the bulge. Figure 2 shows the surface brightness profiles and color gradients in B and R for the 21 galaxies selected for the bulge analysis. Figure 3 present the corresponding near-IR surface brightness profiles and color gradients. Names are correlative to the Impey et al. (1996) catalogue. Dashed lines represent exponential fits, using equation 4. In Figure 2, we include the fitted parameters μ_0 in B and R, expressed in mag arcsec^{-2}, and h, the scale length, expressed in kpc. Vertical lines in the panels of color gradients, represent approximated boundaries for *pure* bulge and disk components, computed visually. Light and color profiles extend up to the radius where the 1σ isophote is reached. For 16 out of 21 galaxies the bulge component can be fitted in the optical by an exponential profile (equation 3) instead than a de Vaucouleurs profile (equation 5). In the near-IR, 14 out of 21 galaxies, are well fitted by two exponentials. The radius separating the bulge and the disk components is estimated visually, and then computed using a simultaneous exponential fit for the bulge and the disk. Note that 5 galaxies which are better fitted in the optical by exponential profiles are however better fitted by $r^{1/4}$ profiles in the near-IR. Also note that some galaxies with good fits in the near-IR are not fitted in the optical neither by an exponential neither an $r^{1/4}$ profile (see below).

In most cases, a fit using the $r^{1/4}$ law was unsatisfactory for the central part of the galaxies. This functional form gives overestimates the bulge central brightness μ_0(bulge), as has been noted by Beijersbergen, de Blok & van der Hulst (1999) and Galaz et al. (2002). The exponential fit gives better results for our sample of galaxies. Five galaxies present no definite optical detection for the disk, and therefore no fitting was possible. For galaxy 473, no acceptable fit was possible to obtain in these bands. For galaxy 264 we were unable to derive a good fit in J and K_s for the bulge component. It is also possible to appreciate for some cases the "flattening" effect in the central zone of the fittings, due to the seeing effect. This effect, however, is so small that it does not change our results[7].

[7]We note that our worst seeing was about 0.9 arcsec, which, considering the average distance of our galaxies, does no affect the brightness nor the color radial profiles.

4. Results and analysis

In this section we present and discuss the color-magnitude and the color-color diagrams. We also use some measured structural parameters which help to study stellar populations in the bulge of our sample galaxies, and analyze possible secular evolution of the galaxies. We also discuss light and color profiles in optical and near-IR bands. We compare our results with those obtained for HSB galaxies by other authors.

4.1. Morphology and color-magnitude diagram

Morphological classification is important because it links those features observed locally with those observed at high-z. Galaz et al. (2002) showed that bluer, gas rich galaxies are more irregular compared to those with lower fractions of HI. Figure 4 show that the 21 face-on nucleated galaxies selected are in fact brighter and generally redder than most of the rest of the sample. It is also true that, concerning light emitted by stars, bluest galaxies have the lowest absolute magnitudes (Figure 4), a trend largely observed in the universe and the first indication that (1) most of the light emitted by very blue galaxies does not come from their continuum stellar emission but from the gas emission, and (2) they present generally an irregular morphology. We note that we have indirectly excluded in our sample dwarf spheroidals (dSph) and dwarf ellipticals (dE). Although these galaxies (especially dSph) present in general low surface brightnesses and red colors, these are not present in our sample, since ours is selected from the Impey et al. (1996) catalog, which lack these types of galaxies. We recall that the Impey catalogue of spirals was built mainly from the APM catalogue (Loveday et al. 1996), which in fact lack dSph and other kind of red but faint galaxies. However, we have checked that the luminosity of bulges hosted by spirals is wide, and the sample include all the Hubble classification for normal spirals (from Sa to late Sc).

4.2. Structural parameters

Here we discuss some structural parameters for the 21 face-on nucleated spirals (Figure 1). Brightness profiles and color gradients are presented in Figure 2 (optical bands) and Figure 3 (near-IR).

Figures 5 and 6 show that our sample follows the same trends observed by the galaxies of de Jong (1995), showing that we have not selected spirals with very bright bulge surface brightness (note the outlier LSB 264 with $h_d = 0.34$, with a large central region compared

to the disk, see Figure 1). From Figure 6 it is clear that galaxies with brighter bulges have brighter disk surface brightness. The range of bulge surface brightness is consistent with the fact that the original sample from the Impey et al. (1996) catalogue (which selects galaxies from the APM survey) includes the total range of spiral galaxies, from Sa to late Sc. We note that our sample of 21 galaxies is in any case a complete sample: these are simply the number of galaxies from our sample with valid B and R photometry which are oriented face-on.

On the other hand, Figure 7 shows the inner 2 kpc $B-R$ color as a function of the disk central surface brightness. This Figure shows that there is no bias or selection effect between color and surface brightness: a wide color range is included in the sample for both the faint and bright end. However, note that there are tight correlations between the HI gas mass (taken from Impey et al. (1996)), the color, the absolute total magnitude and the surface brightness. Figure 8 shows the relationship for these parameters, for the 52 galaxies shown in Table 2. The 21 nucleated, face-on galaxies (black dots) are in fact part of the most massive sample (in terms of the HI content), and with the brightest absolute magnitudes. The color $B-R$ is computed for the inner 2 kpc for each galaxy. Note the tight relationship for the parameters, especially for the absolute magnitudes in both filters B and R. The brighter a galaxy is, the larger the HI mass, the redder the galaxy, and the higher the surface brightness are. These trends in optical bands agree with results of Galaz et al. (2002) in the near-IR bands J and K_s. However, note that one can infer from Figure 8 that LSBGs ($\mu(0) > 21.6$ mag arcsec^{-2}) have faint absolute magnitudes ($M > -16$ mag). This is different to what was found in the near-IR bands (Galaz et al. 2002).

4.3. Color gradients

Figure 2 presents the surface brightness and color profiles for the 21 face-on nucleated galaxies. Contrary to what was expected, a high fraction of them (10 galaxies out of 21) present a significant inverse color gradient near their center: the color is redder as the distance to the bulge increases. Could this due to dust present in the disk, which redden the color? If this is not the case, could this be a sign of bulge secular evolution in these spirals, i.e., the bulge was formed after the disk?

Currently, many authors argue that the dust content of the disk in LSB galaxies is low (de Blok, van der Hulst & Bothun 1995), and there is some evidence suggesting that some LSB galaxies are dust poor (Beijersbergen, de Blok & van der Hulst 1999). The combined near-IR and optical photometry shows that these galaxies in fact do not have significant amounts of dust in their most inner parts and their bulge neighborhood (see however Holwerda et al. (2005)), and is unable to reproduce the observed color gradients

(e.g. galaxies 196, 213, 345, 463, 468, 470, 471, 473, 484 and 488, see also discussion in §5.1).

However, near-IR color gradients (Figure 3) show that most of the near-IR surface brightness profiles are (1) well fitted for all their extension solely by the combination two exponential profiles, and (2) color gradients are null. Although this last point could support by itself the hypothesis that reddening is not strong in these galaxies or, at least, the dust abundance is similar along the galaxy components (bulge or disk), a large amount of dust seems not to change necessarily the near-IR colors, and therefore the color gradient, as shown in §5.1.

Therefore it is likely that for our selected sample of spirals and LSB galaxies, the nature of these color gradients is not the dust content, either for the galaxies presenting "normal" color gradients (i.e. galaxies with nearly flat or red to blue color gradients), as well as for those presenting inverse color gradients.

For galaxies with normal color gradients, we support the hypothesis that observed color gradients are generated by a canonical stellar distribution along the radial axis: the stellar populations more distant to the bulge are metal poorer and/or younger compared to the stellar population closer to the bulge. This scenario agree with the idea that the bulge is formed first from accretion, and the disk form after, and does not agree with stellar formation occurring progressively from the disk to the center of the galaxy mass distribution (the bulge secular evolution). At first impression, the bulge secular evolution does not match with the observation that some early type galaxies were already formed at high-z ($z \sim 2$), following recent results from the Hubble Ultra Deep Field (HUDF). However, there could be an undetermined fraction of bulges in the HUDF hosted by undetectable disks with central surface brightnesses well below the limiting surface brightness reached by the ACS at the HST[8]. These spiral galaxies could be therefore misclassified as pure ellipticals (compact ones). In spite of this evidence, we wish to confront the model of bulge secular evolution with our analysis from the structural parameters.

Assuming that the internal dust extinction is not the main reason for the inverse color gradients for the 10 galaxies of our sample, the hypothesis of secular evolution for these galaxies should be seriously considered. We investigate and discuss this hypothesis in the next section, especially in scope of the results for the near-IR light profiles and color gradients.

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[8]This surface magnitude "drop out" selection for high-z galaxies is mainly due to the cosmological dimming factor $(1+z)^{-4}$ for the surface brightness (Tolman 1930).

5. Discussion

5.1. Application of the spectrophotometric model in the context of bulge and disk formation

Colors observed in cores of spiral galaxies selected for this study can be compared to those predicted by spectrophotometric models of galaxy evolution. These models predict, among many other quantities, the integrated colors and ages for stellar populations, for a given range of metallicity.

The synthesis models use a wealth of information about stellar evolution, which include stellar evolutionary sequences, spectral libraries, and a number of tunable parameters such as the initial mass function (IMF) slope, the stellar formation rate (SFR), and current results of semi-empirical theories of chemical enrichment. They allow the computation of spectral energy distributions for an ensemble of stars (a galaxy), and some selected spectral indices and colors, as a function of age and metallicity. The model used here is that of Bruzual & Charlot (2003), which provides results as a function of the mean age, after an instantaneous burst of stellar formation and subsequent exponential (increasing and decreasing) SFRs, for a metallicity range 0.005–2.5 $Z_\odot$. The IMF used is that of Scalo (1986). The Salpeter (1955) IMF gives similar results. Different amplitudes for the star formation are indicated by different exponents in the SFR, which can increase or decrease exponentially from an initial time t_0 to present, and $\tau > 0$ for SFRs $\propto e^{-t/\tau}$, and $\tau < 0$ or SFRs $\propto e^{(t_0-t)/\tau}$. Each one of these exponents is associated with a mean stellar age for the corresponding stellar population. Giving the joint evidence of WMAP that the last electron scatter was about 13.7 billion years ago, and stars formed 200 million years after (Benett et al. 2003), it is reasonable to fix model star formation 12 Gyrs ago. The characteristic time τ is related with the stellar formation efficiency. For example, the most efficient SFR is set with $\tau = -1$, where most of the population is formed recently, and has 1 Gyr mean age. Alternatively, for the less efficient stellar formation we use $\tau = 0$, corresponding to an instantaneous burst, i.e., all stars formed at the same time, with no further stellar formation processes.

As discussed in the next section, current evidence suggests that possible paths of bulge formation in HSB galaxies are closely related to the relative size of bulges (Courteau, de Jong & Broeils 1996). Bulges of HSB spirals, large and prominent, share some properties in their stellar populations with those featured by medium size elliptical galaxies. More precisely, both populations of stars exhibit the same age and metallicity (old and metal rich). In contrast, *small* bulges present in a number of HSB spirals clearly exhibit different abundances and probably have different ages compared with medium size ellipticals, *but* similar properties compared with stellar populations in *disks* (younger and less metal rich

than core of ellipticals). Are these features also observed in LSB galaxies?

The color-color diagram $J - K_s$ vs. $B - R$ for the inner part of the bulges (radius < 2 kpc) and the corresponding color-color model grid are shown in Figure 9. Black dots represent bulge colors of our 21 nucleated, face-on spirals and open circles of Peletier & Balcells (1996) data, corresponding to a B, R, J, and K_s photometry for a sample of bulges hosted by spirals. The major change in $J - K_s$ is for a $Z_\odot$ population, which varies only ~ 0.15 mags for an increase of mean age from 1 Gyr to 12 Gyrs. All points have been corrected from atmospheric and Galactic extinction, this last using the Schlegel, Finkbeiner & Davis (1998) extinction maps.

Figure 10 shows the color-color diagram using colors of the *inner 2 kpc* for the 21 selected galaxies, superimposed over the Bruzual & Charlot (2003) model grid as in Figure 9. Colors have been corrected using the Galactic extinction maps of Schlegel, Finkbeiner & Davis (1998), and internal extinction supposing a maximum in $B-R$ reddening of 0.3 mag (see next paragraph). This color-color diagram suggests that stellar populations of small bulges (open symbols), defined by the bulge to disk scale length ratio $h_b/h_d < 1\sigma$ (see next section) compared to average, appear slightly younger and clearly metal poorer than stellar populations hosted by larger bulges ($h_b/h_d > 1\sigma$, filled circles), except for three bulges with metallicity above $Z_\odot$. This is expected from the hypothesis of secular evolution: bigger bulges are result of larger accretion time, generating more stellar formation in the past and then the present stellar population is more metal rich compared to what is found in smaller bulges. From Figure 10 it is also apparent that LSBGs[9] tend to have smaller bulges (open squares), which is also consistent with secular evolution: a smaller stellar stellar density (which define a LSBG) could impact on a slower secular evolution, forming a smaller bulge as see today. In summary, our data suggest that metal poor bulges tend to be smaller than metal rich bulges, on average.

This result *suggests* that the relation between the relative size of HSB spiral bulges and their eventual secular evolution, could be also applicable to LSB spirals, given the melting HSB/LSB fraction in our sample. From Figure 10, it is clear that $J-K_s$ is a good metallicity indicator (Galaz et al. 2002), and relatively insensitive to stellar populations of different mean ages.

A very hard problem to solve is the amount of internal extinction which reddens each particular galaxy. The optical color $B - R$ is the most affected by dust and/or gas. In

[9]Note that here the term HSB galaxy is defined for galaxies with $\mu(0, B) < 22.0$ mag arcsec^{-2}, as usual, but note however that all galaxies are just above or tiny below this limit, and hence we really do not have HSB galaxies strictly speaking.

principle, the amount of extinction could be very different from one galaxy to another. However, it is important to keep in mind that in our case: (1) colors are computed for the central part of the galaxies, in particular for the bulges, where dust is not generally present; therefore it is reasonable to assume that extinction should not be too large in these regions. (2) The selected galaxies are oriented face-on, and then the line of sight is not passing through a thick portion of the corresponding galactic disk and/or spiral arms; thus, the extinction should not be large. However, when we observe the color-color diagram at face value, specifically the $B-R$ color, one has the impression that $B-R$ is too red compared to the models, appealing for a possible significant extinction. The key is to estimate the modulus of the extinction vector in the color-color diagram using some reasonable assumptions. For this we use the spectrophotometric model PEGASE (Fioc & Rocca-Volmerange 1997), which offer the possibility to consider extinction, by allowing to generate a set of synthetic spectra with different amounts of dust, which are convolved with synthetic filters to estimate the reddening vectors in the $J-K_s/B-R$ plane. Results show that increasing the dust content of the bulge component by as much as 60% from a nominal value, imply an increase in $J-K_s$ and $B-R$ colors by no more than 0.15 mag over the full range of colors (see Figure 11). Each symbol in Figure 11 represent a different evolutionary stage (from 0.5 Gyr to 13 Gyr, from left to right) with a different metallicity, consistent with stellar evolution, nucleosynthesis and supernova rate. For each point or square, the dust *surface density* is 60% larger than a fiducial dust surface density at the same age.

In summary, we conclude that the internal extinction should not be large, *at least* in the regions where our color indices were calculated, i.e. in the bulges. This is discussed by other authors: for example Bell et al. (2000), precisely claim that dust does not have a large impact on the color of *face-on* nucleated LSB spirals.

An almost negligible extinction in $J-K_s$ and small extinction in $B-R$ in the bulge (a maximum of ~ 0.3 mag) would primarily affect our age estimates but not our metallicity determinations. Note in Figure 11 that there is an interval of age where the index $B-R$ has a *lower* reddening than $J-K_s$, probably due to a saturation effect on the $B-R$ index, which seems to continue for $B-R \gtrsim 1.2$, reflected in the decease of the color $B-R$; while the optical thickness increases, the $B-R$ color may saturate and the bulge gets optically thick in both bands. At the same time, however, the galaxy is optically thin in J and K_s, although the opacity τ increases and $J-K_s$ still reddens.

Bulges of HSB galaxies appear to have less scattered colors than those observed in spirals and LSB galaxies of our sample, as shown in the color-color diagram. Their metallicity range is $1.0\mathrm{Z}_\odot < \mathrm{Z} < 2.5\mathrm{Z}_\odot$ and ages are around 8.6 Gyr. One can compare these results with those obtained for high surface brightness (HSB) bulges. For example, the higher metallicity

measured for bulges of HSB spirals of Peletier & Balcells (1996), represented as open circles in Figure 9, is in agreement with the fact that these contain evolved, enriched old stellar populations. However, our data disagree with the metallicity measured for the HSBs in Peletier et al., in the sense that they claim solar or near solar metallicities using the models of Vazdekis et al. (1996), and the model we use gives super-solar metallicities. What probably makes the difference between Vazdekis et al. models and the Bruzual & Charlot models used here is the contribution of the post-AGB stars and other advanced stages of stellar evolution.

In the case of our normal and LSB spirals, we obtain that bulges show solar or subsolar metallicities, and ages as young as 4 Gyrs. This supports well known results where LSBs appear as metal poor systems (de Blok & van der Hulst 1998; Bell et al. 2000). We also measure systematic bluer color for LSB bulges, as compared to those bulges of HSB galaxies (see Figure 9), both in $B - R$ and $J - K_s$.

5.2. Bulge formation scenarios for HSB and LSB galaxies

One of the fundamental questions about galaxy formation, and in scope of the observed stellar population content at a given redshift, is the possible *chronological* order in which the different structural components of a spiral galaxy form. This chronology clearly imposes constraints to the galaxy formation models and to the subsequent stellar evolution of the different building blocks of galaxies. In this context, one can ask about the order in which the two major components of spirals, namely the bulge and the disk, are formed.

Many studies have pointed out that the bulges of grand design spirals (like M31) share many properties with those observed in medium size elliptical galaxies. Among these properties we can mention the so-called $D_n - \sigma$ (Dressler 1987) and the fundamental plane (Bender, Burstein & Faber 1992) relations. Furthermore, Jablonka & Arimoto (1996) found that bulges of late type spirals (Sc) follow the same Mg-σ relationship defined for early type ones, suggesting that their bulges share the same mass-metallicity relationship as observed in elliptical galaxies. These results, along with the kinematical evidence provided by velocity dispersions, support the idea that medium-size elliptical galaxies accrete gas from the surrounding environment, forming a disk and then building up a spiral galaxy (Kauffmann, White & Guiderdoni 1996). In this way, stars in bulges of spiral galaxies should be similar to those in elliptical galaxies, i.e., old and metal rich, differentiating from those populating disks.

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with small bulges, indicate that they share many properties with their corresponding disks. For example, many bulges of spiral galaxies are much better fitted by exponential profiles than by de Vaucouleurs profiles (de Jong 1996), and also many of them present a disk like kinematics (Kormendy 1993). These results suggest that small bulges of spiral galaxies were built from stars already formed in the corresponding disks, which in turn indicate that stars currently populating such bulges should be similar to those stars populating the corresponding disks (relatively young and metal rich, but less than those populating elliptical galaxies), and therefore are different to stars present in elliptical galaxies. In fact, the excellent work of Trager et al. (1998) based on stellar population models and spectroscopy of the central region of Sa-Sd spirals, provides evidence in favor of bulge formation in late spirals triggered by gravitational interaction in their disks. One can argue that the above evidence supports secular evolution. Are these results also valid for some LSB spiral galaxies?

The hypothesis of secular evolution (that disk form first, and the bulge emerges naturally from this (Courteau, de Jong & Broeils 1996)), imply that the disk and bulge scale lengths are correlated or, in other words, the bulge-to-disk (B/D) ratio is independent of galaxy type. If the sequence of galaxy morphology is continuous in terms of surface brightness, naturally the statement should be valid for both LSBs and HSBs. This correlation is supported by some models (Combes et al. 1990; Struck-Marcell 1991), and depends mainly on the relative timescales of the star formation and the viscous transport, and on the strength of the total angular momentum. Also, one can predict that secular evolution will produce in many cases what is called pseudobulges: disks agglomerate to the center of the galaxy, producing a high density of stars which structurally are similar to bulges, and share similar stellar population properties observed in the disk. One of the observed properties is that the entire surface brightness profile can be fitted by a combination of two exponential profiles. This is exactly what we obtain for most of the optical profiles (14 galaxies, Figure 2) and almost all the near-IR profiles (16 galaxies) as presented in Figure 3. Thus, one can argue that our data support the evidence not only of secular evolution, but also of the formation of pseudobulges.

Figure 12 presents the correlation between disk and bulge scale lengths for a set of spirals. Filled circles correspond to our data and open ones are those compiled by Beijersbergen, de Blok & van der Hulst (1999). A Kolmogorov-Smirnov (KS) test show that the idea that the two variables are not correlated is rejected at the 98% level. This could suggest that disk and bulge formation were coupled (Beijersbergen, de Blok & van der Hulst 1999). Note that there is *no correlation* between the bulge-to-disk scale lengths and the central surface brightness of the disk, as shown by Figure 13. In this Figure, it is apparent that most scale lengths ratios are around 0.05 and 0.2, with four outliers with $h_b/h_d \geq 0.3$. These correspond to galaxies 470, 447, 324 y 264. They do have larger bulges, and well defined surface brightness profiles, except galaxy 264 (with no acceptable bulge fitting in the near-

IR), and do not present any other different feature from the rest of the sample, except galaxy 470, which present inverse color gradient in its bulge.

The correlation between scale lengths of disks and bulges shown in Figure 12 suggests that the formation of these two components is coupled, supporting the hypothesis that disks form first and bulges emerge after and, the larger the disk, the larger the corresponding bulge scale length. The restricted range of $\log h \sim 0.1$ for the bulge and disk scale lengths ratio (Figures 5 and 13) is the same as used as an argument for secular evolution models (Courteau, de Jong & Broeils 1996): self consistent numerical simulations of disk galaxies evolve toward a double exponential profile with a typical bulge-to-disk ratio ~ 0.1 (Friedli & Benz 1995), suggesting that bulge formation is triggered by disk instability. If this scenario is correct, then bulges should be relatively young. More recently, Mayer & Wadsley (2004) presented numerical simulations showing that bars can be formed in massive LSBs under some specific constraint of disk density and gas temperature. These bars, short in length compared to the halo and quite unstable in time, *necessarily* trigger the formation of a bulge component, similar to that present in many LSBs observed in red and near-IR bands by O'Neil, Bothun & Schombert (2000) and Galaz et al. (2002).

For our sample of 21 galaxies (Figure 12, filled circles), we define the relative size of their bulges using the ratio between their scale lengths (h_b/h_d), which is naturally correlated with the Hubble type. A small bulge has a ratio h_b/h_d below 1σ compared to average (a Hubble type typically a Sc). A large bulge has a h_b/h_d above 1σ respect to the average (a Hubble type Sa or Sb). Although we do not observe a tight relationship between these two scale lengths (particularly if we consider the 3 outliers marked in the figure), the trend is clear and similar to what has been observed by Beijersbergen, de Blok & van der Hulst (1999) (open circles), suggesting a possible secular evolution. Both, h_b and h_d, follow approximately the same trend, except that our slope ($< h_d/h_b >= 8.18$, $\sigma = 5.5$) is somewhat different to that of Beijersbergen, de Blok & van der Hulst (1999), indicated as a dashed line in Figure 12 ($< h_d/h_b >= 9.98$, $\sigma = 3.78$). We therefore define a bulge as "small" if $h_d/h_b > 13.8$ and "large" if $h_d/h_b < 2.68$, considering our average slope $< h_d/h_b >$ and its measured standard deviation. Note that we are not excluding any galaxy from our sample following this criterion and, although the number of galaxies is small, trends are observed clearly for the scale length ratios. In Figure 14 we show a similar correlation as in Figure 12, but for the J and K_s near-IR bands. The correlation holds and in fact, the scatter is even smaller. However, near-IR bulge scale lengths are larger compared to their optical counterparts. This is natural if we think that the bulge is metal rich compared to the disk and with older stellar populations. Therefore the bulge appear brighter and larger in the near-IR.

In summary, (1) the observed relationship between h_b, h_d and its ratios, (2) the inverse

color gradients in the optical, (3) the double exponential fit for most of the galaxies, both in the optical and the near-IR bands, and (4) the almost null $J - K_s$ color gradients, support the secular evolution hypothesis.

However, the fact that most bulges are redder than disks (see Figure 2), favors at first impression the scenario where bulges were formed before disks. Andreakis (1998) showed that, in this case, it should also exist a correlation between the bulge and disk scale lengths, similar to the correlation observed in Figure 12. If this last scenario is correct, bulges should be relatively old compared to disks. Nevertheless, note that even two stellar populations formed at the same time, but with different surface density (e.g. the bulge and the disk, the first a denser one) could evolve differently. A larger surface density would favor a more efficient stellar formation, and therefore a larger SFR at the bulge, resulting in a redder bulge compared to the disk. It is worth noting that the observed trend does not strongly support the hypothesis that HSB galaxies are progenitors of LSB galaxies, since we do not observe that HSB galaxies are bluer than LSB galaxies. In fact, bulges of LSB galaxies appear metal poor compared to bulges of HSB galaxies (see Figure 9).

One of the most striking features in the optical color profiles, is the inverse color gradient in the central zone in 11 of the 21 galaxies, i.e. the color is bluer as radius decreases. Boissier et al. (2003), comparing data of LSB galaxies with chemical and spectrophotometric models of galaxy evolution, arrive to the conclusion that, given the large scatter observed in the LSB galaxy properties, it is necessary to introduce both starburst events as well as interruption of ongoing stellar formation processes, in order to match models with observations. These events could arise by gravitational interactions, causing then inverse color gradients. Menanteau, Jimenez & Matteucci (2001), studying a HST dataset of 77 early-type galaxies presenting this inverse color gradient, use a multizone single-collapse model which account for the observed blue cores. The model adopts a broad spread in formation redshifts for elliptical galaxies, allowing some of these galaxies to begin their formation up to 1 Gyr before the redshift of observation. Therefore, the single-zone collapse model produces cores that are bluer than the outer regions because of the increase of the local potential well toward the center, which makes star formation more extended in the central region of the galaxy than in the outer parts[10]. Could these inverse color gradients be an evidence of secular evolution? The answer to this question is directly related to the age-metallicity degeneracy. Indeed, bulges can be redder because they are older, more metallic or more affected by dust reddening. The inverse color gradients presented here would support secular evolution, if it would be possible to show that these gradients are exclusively due to metallicity (Galaz et

[10]Note that a recent by Menanteau et al. (2004) present evidence arguing that elliptical blue cores are due to the presence of an AGN.

al. 2005). However, further evidence already discussed here, namely (1) the relationship between h_b, h_d and its ratios, (2) the double exponential fit for most of the face-on nucleated galaxies, both in the optical and the near-IR bands (pseudobulges?), and (4) the almost null radial $J - K_s$ color gradients, support the secular evolution hypothesis. The null $J - K_s$ gradient suggests that the bulge and disk stellar population are much more similar, i.e., that their metallicity is uniform (see Figure 10 or 9).

6. Conclusions

We have presented an analysis of a sample of 21 face-on nucleated HSB and LSB spirals selected from the catalogue of Impey et al. (1996). We have studied their bulges colors and structural parameters in scope of bulge and disk formation, obtaining the following relevant results.

First, bulge and disk scale lengths appear to be marginally correlated, weakly supporting a secular evolutionary process between these two components. However, the relationship between the bulge and disk sizes for HSB seems (B/D ~ 0.1) to be identical to that observed for LSB galaxies, which can be understood in a general context of bulge and disk formation. Also, our results agree with the analysis both from observations presented by Courteau, de Jong & Broeils (1996), and from models by Mayer & Wadsley (2004), suggesting that bulges could be formed by bar instabilities in early stages of disk evolution. The recently discovered red LSBs, with a notable non-axisymmetric structure and bulge components, are in agreement with many of the LSB models which incorporate massive disks.

Second, structural analysis shows that LSB galaxies follow the same trends (bulge size, disk size, scale lengths, etc.) observed in HSB galaxies, which constitutes evidence that, at least in their structure, LSB galaxies are not a different type of galaxy. On the other hand, we rule out the possibility that HSB galaxies are progenitors of LSBs, basically using the fact that the colors of their bulges are redder compared to those observed in LSBs.

Third, almost half of our sample shows inverse gradients in their $B - R$ radial color profiles (bluer color toward center). Although there is not a straightforward explanation for this, this analyze is key to understand correctly the possible chronology of events which lead to the formation of disk and bulge. Our near-IR surface brightness profiles, do not show inverse color gradients, but present null color gradients which, with the evidence that almost all the light profiles are well fitted by exponential forms (in the optical and in the near-IR), support the secular evolution for these face-on nucleated galaxies and the existence of pseudobulges.

Fourth, using a spectrophotometric model of galaxy evolution, and using the fact that the color index $J-K_s$ is metal sensitive, we find evidence suggesting that bulges of LSBs are metal poor compared to those hosted by HSBs, extending the overall result from emission line analysis that stellar formation regions of LSBs are also metal poor compared to HSB ones (de Blok & van der Hulst 1998; Galaz et al. 2005). Using the synthesis model PEGASE, we have shown that a possible small amount of dust in the bulges does not play an important role on the bulges color and structural parameter properties, and that the extinction in $B-R$ is smaller than 0.3 mags. We arrive to the same conclusions of Bell et al. (2000). Moreover, we obtain that bulges hosted by LSB galaxies tend to be small ones. In turn, small bulges are metal poor, compared to larger bulges. This agree with the secular evolution model, in which bulges are built up secularly from the disk, where small bulges have been subject of weak stellar formation processes and slower accretion, leading to a metal poor stellar population in average.

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Figure captions

Fig. 1.— Mosaic showing B images of the 21 selected spirals for this study. Note that all of them present bulges and are face-on, except galaxy 515, for which we have estimated an inclination of 45 deg, and therefore increasing the surface brightness, due to inclination i, by $2.5\log(b/a)$, where $b = acos(i)$, and a the major axis.

Fig. 2.— Optical surface brigthness and color profiles for all 21 galaxies selected for the analysis. Top panels for each galaxy represent the surface brightness profile in the B and R band. We include the central surface brightness of both the disk and bulge component, from the linear fit represented by the dashed lines. The bottom panel represent the $B-R$ color gradient. Vertical lines mark the approximate boundaries obtained visually of the pure bulge and disk components. Dotted lines indicate the central $r^{1/4}$ fit.

Fig. 3.— Near-IR surface brightness profiles and color gradients for the 21 face-on nucleated galaxies. Most of the galaxies are well fitted by a combination of two exponetial profiles (disk and bulge), except galaxies 59, 100, 224, 470, and 471, which bulge is better fitted by a $r^{1/4}$ profile. Upper curves show the K_s profile and lower curves the J profile. For clarity, dashed lines show the bulge and disk exponential fits only for one of the two bands. Solid lines show the corresponding bulge + disk fit. The vertical line indicate the maximum error for the computed surface brightness and color, for each panel.

Fig. 4.— B absolute magnitude as a function of the $B-R$ color for spirals investigated in this paper. Open circles denote the 21 face-on spirals and filled circles denote other spirals and irregular galaxies. The error bar in the bottom right side of the figure indicate the maximum error in absolute magnitude and color.

Fig. 5.— Disk central surface brightness in the B band as a function of the disk scale length. Black dots represent our sample and open circles galaxies from de Jong (1995). Note the outlier LSB 264, with a disk scale length of 0.34. This is a galaxy with a dominant bulge respect the disk (see Figure 1).

Fig. 6.— Bulge central surface brightness in the B band as a function of the disk central surface brightness in the B band. Symbols as in Figure 5.

Fig. 7.— Inner 2 kpc $B-R$ color as a function of the disk central surface brightness in the B band. Symbols as in Figure 5.

Fig. 8.— Figures presenting the relationship between the HI gas mass and various measured parameters. (a) as a function of the color $B-R$ for the inner 2 kpc of each galaxy. Redder

galaxies tend to be massive in HI; (b) and (c) as a function of the total absolute magnitudes in the B and R bands, respectively. Brighter galaxies are also more massive in HI; (d) as a function of the R surface brightness. Black dots represent the 21 nucleated, face-on galaxies. Galaxies with low surface brightnesses tend to have small HI masses, as expected.

Fig. 9.— $J - K_s$ vs. $B - R$ color-color diagram for the bulge inner 2 kpc of our selected galaxies (black dots), and for those HSB galaxies compiled by Peletier & Balcells (1996) (open circles). The grid corresponds to the colors predicted by GISSEL96 spectrophotometric model of galaxy evolution by Bruzual & Charlot (2003). Horizontal lines represent different metallicities and vertical lines different ages since burst (see text for detail).

Fig. 10.— $J - K_s$ vs. $B - R$ color-color diagramme for the bulge inner 2 kpc, for small bulges (open symbols) and for large bulges (filled symbols). The grid as in Figure 9. It is apparent that small bulges appear younger and less metallic compared to large ones. Small bulges tend to be metal poor compared to large bulges. Also note that LSB galaxies (squares) tend to have small bulges. Colors are corrected for Galactic extinction using the maps of Schlegel, Finkbeiner & Davis (1998) and for internal extinction (see text for details)

Fig. 11.— $B - R_c$ (black points and solid line) and $J - K_s$ (open squares and dashed line) color difference for an evolving bulge when 60% more surface density of dust is considered initially. The fiducial dust content is taken as the dust surface density of the Galaxy bulge. Each point is the color and color difference at a given age. Numbers indicate age after bulge formation. From one evolutionary stage to the following, metallicity and dust surface density is changing according to stellar evolution and winds.

Fig. 12.— Disk scale length in the B band (h_d, in kpc) as a function of the bulge scale length in the same band (h_b), for the galaxies in our sample (black dots) and by Beijersbergen, de Blok & van der Hulst (1999) (open circles). Lines represent the h_d/h_b average ratio for our sample (solid line) and such for the sample of Beijersbergen, de Blok & van der Hulst (1999) (dashed line).

Fig. 13.— Bulge to disk scale length ratio, as a function of the disk central surface brightness (B band). Solid circles denote results for the face-on sample and open circles other spirals and irregular galaxies.

Fig. 14.— Near-IR disk scale length (h_d in kpc) as a function of the bulge scale length (h_b in kpc), for the galaxies in our sample. Filters as indicated in each panel.

Table 1. Solutions for the photometric calibration given by equations 1 and 2.

Night	Z_B [a]	k_B [b]	C_B [c]	Z_R [a]	k_R [b]	C_R [c]
28-29 May 2000	-0.49(0.02)	-0.20(0.01)	0.15(0.01)	-0.61(0.03)	-0.10(0.02)	0.01(0.016)
29-30 May 2000	-0.58(0.57)	-0.13(0.50)	0.15(0.02)	-0.72(0.53)	-0.04(0.45)	0.01(0.013)
30-31 May 2000	-0.65(0.43)	-0.17(0.32)	0.15(0.01)	-0.69(0.36)	-0.06(0.33)	0.01(0.011)
25-26 Aug 2000	-0.91(0.09)	-0.13(0.02)	0.06(0.01)	-0.42(0.15)	0.01(0.08)	0.01(0.009)
26-27 Aug 2000	-0.89(0.14)	-0.16(0.10)	0.07(0.01)	-0.53(0.14)	0.01(0.11)	0.02(0.012)
07-08 Apr 2002	-0.98(0.18)	-0.08(0.17)	0.02(0.04)	-0.46(0.23)	-0.01(0.23)	-0.06(0.044)
08-09 Apr 2002	-0.89(0.11)	-0.22(0.09)	0.07(0.01)	-0.45(0.10)	-0.09(0.08)	-0.01(0.013)

[a] Photometric zero point in the respective filter with its r.m.s. error in parenthesis.

[b] Extinction coefficient in the respective filter with its r.m.s. error in parenthesis.

[c] Color term coefficient in the respective filter with its r.m.s. error in parenthesis.

Table 2: B and R magnitudes and colors for all spirals in the sample.

No.	Name	μ_B(2kpc)	μ_R(2kpc)	M_B	M_R	$(B-R)_C$	$(B-R)_T$	log($M_{HI}/M_{\odot}$)	Type	D_{eff}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
4	0013-0034	20.02(0.06)	18.28(0.07)	-20.810.05)	-22.02(0.06)	1.69(0.09)	1.33(0.08)	10.18	Sc	36.8
16	0027+0134	22.22(0.06)	21.13(0.07)	-17.20(0.06)	-18.10(0.07)	1.03(0.09)	0.85(0.08)	8.65	Sd	18.8
36	0104+0140	20.63(0.06)	19.09(0.07)	-18.06(0.08)	-19.26(0.07)	1.50(0.10)	1.17(0.08)	8.74	Sb	10.2
59	0121+0128	19.57(0.06)	17.87(0.07)	-20.11(0.06)	-21.66(0.05)	1.64(0.10)	1.67(0.09)	9.64	Sc	80.4
100	0233+0012	22.44(0.06)	21.28(0.07)	-17.19(0.05)	-18.16(0.05)	1.11(0.09)	1.09(0.08)	8.89	Sc	46.8
126	0311+0241	20.62(0.06)	19.74(0.07)	-19.23(0.06)	-20.09(0.08)	0.73(0.09)	0.89(0.08)	9.57	Irr	12.2
146	0336+0212	23.15(0.06)	22.16(0.07)	-16.24(0.08)	-17.07(0.07)	0.80(0.09)	0.65(0.08)	8.62	dIn	24.4
196	0913+0054	20.04(0.01)	18.65(0.02)	-19.71(0.07)	-20.97(0.06)	1.34(0.02)	1.21(0.02)	9.68	Sm	16.4
200	0918-0028	21.25(0.01)	20.23(0.01)	-17.78(0.05)	-18.79(0.05)	0.98(0.02)	0.95(0.02)	8.63	Sb 16.2	
207	0929+0147	20.77(0.10)	18.57(0.13)	-19.88(0.06)	-21.50(0.05)	2.07(0.16)	1.49(0.14)	10.03	Sc	26.6
213	0954+020	20.63(0.10)	19.62(0.13)	-19.48(0.04)	-20.43(0.07)	0.97(0.16)	0.90(0.14)	9.59	Sc	18.6
224	1007+0121	20.94(0.01)	18.80(0.02)	-21.23(0.06)	-22.81(0.05)	2.08(0.02)	1.52(0.02)	10.69	Sc	16.2
225	1008+0128	21.05(0.01)	19.57(0.02)	-19.61(0.05)	-20.72(0.07)	1.41(0.02)	1.03(0.02)	9.87	Irr	17.4
242	1030+0252	19.90(0.06)	18.63(0.05)	-19.87(0.08)	-21.04(0.07)	1.22(0.08)	1.12(0.07)	9.65	SB	15.2
253	1036+0158	22.47(0.01)	21.58(0.01)	-10.62(0.04)	-11.47(0.05)	0.83(0.02)	0.79(0.02)	7.62	dIn	23.8
264	1043+0202	24.24(0.05)	23.25(0.05)	-10.71(0.06)	-11.69(0.07)	0.91(0.07)	0.90(0.07)	7.73	dIn	13.6
266	1047+0131	24.07(0.01)	23.04(0.02)	-12.68(0.06)	-13.60(0.05)	0.95(0.02)	0.84(0.02)	7.94	dI	15.6
270	1050+0253	22.81(0.01)	22.24(0.01)	-12.80(0.05)	-13.39(0.04)	0.50(0.02)	0.52(0.02)	8.02	dIn	17.4
295	1124-0043	22.39(0.01)	21.62(0.02)	-13.08(0.05)	-13.83(0.06)	0.73(0.02)	0.70(0.02)	8.10	dIn	25.8
308	1156+0254	23.91(0.01)	22.92(0.01)	-14.36(0.04)	-15.26(0.05)	0.93(0.02)	0.84(0.02)	8.72	Sc	28.4
324	1211+0226	21.53(0.05)	19.80(0.05)	-20.22(0.07)	-21.40(0.08)	1.69(0.07)	1.14(0.07)	10.19	Sc	29.8
329	1216+0029	24.14(0.10)	23.40(0.15)	-10.67(0.12)	-11.30(0.17)	0.70(0.19)	0.59(0.16)	7.55	dIn	21.6
330	1217+0103	22.25(0.01)	21.34(0.01)	-16.13(0.04)	-16.89(0.05)	0.88(0.02)	0.73(0.02)	8.62	Sm	34.2
345	1226+0105	20.38(0.01)	19.23(0.02)	-19.68(0.05)	-20.82(0.05)	1.11(0.02)	1.10(0.02)	10.26	Sc	25.8
349	1228+0157	23.00(0.01)	22.16(0.01)	-12.97(0.04)	-13.82(0.04)	0.81(0.02)	0.82(0.02)	7.75	dIn	23.8
365	1257+0219	22.40(0.01)	21.59(0.02)	-11.55(0.05)	-12.53(0.07)	0.76(0.02)	0.94(0.02)	7.61	dIn	26.2
370	1300+0144	21.35(0.06)	19.78(0.06)	-19.86(0.08)	-21.12(0.07)	1.53(0.08)	1.22(0.07)	9.98	Sc	15.0
377	1310-0019	22.44(0.05)	21.11(0.05)	-19.12(0.07)	-20.10(0.07)	1.28(0.07)	0.94(0.07)	9.84	Sc	19.4
378	1315+0029	21.92(0.01)	20.87(0.02)	-18.59(0.04)	-19.48(0.05)	1.00(0.02)	0.84(0.02)	9.94	Sm	25.6
380	1321+0137	20.79(0.01)	19.06(0.02)	-20.45(0.06)	-21.77(0.07)	1.69(0.02)	1.27(0.02)	9.64	Sm	13.4
384	1326+0109	23.84(0.09)	22.70(0.13)	-16.45(0.13)	-17.33(0.15)	1.09(0.16)	0.83(0.14)	8.74	dI	35.8
385	1327+0148	23.24(0.01)	22.49(0.01)	-12.49(0.05)	-13.24(0.06)	0.70(0.02)	0.71(0.02)	7.49	dIn	21.4
393	1350+0022	22.44(0.01)	21.63(0.01)	-17.62(0.04)	-18.35(0.04)	0.74(0.02)	0.67(0.02)	8.84	Sm	8.6
398	1353+020	23.51(0.09)	22.88(0.13)	-15.91(0.10)	-16.49(0.16)	0.58(0.16)	0.52(0.14)	8.96	dI	16.6
400	1357-0017	23.89(0.05)	22.89(0.05)	-15.16(0.07)	-15.99(0.08)	0.93(0.07)	0.77(0.07)	8.74	Sm	20.2
407	1401+0108	21.27(0.01)	19.90(0.02)	-19.96(0.04)	-20.88(0.05)	1.31(0.02)	0.86(0.02)	9.66	Sb	11.2
410	1405+0006	21.39(0.01)	20.27(0.02)	-18.99(0.05)	-19.85(0.06)	1.06(0.02)	0.79(0.02)	9.73	Sb	12.4
424	1433+0249	24.12(0.01)	23.06(0.02)	-13.04(0.05)	-14.02(0.07)	1.01(0.02)	0.92(0.02)	8.03	dI	30.2
433	1438+0049	23.32(0.10)	21.06(0.15)	-15.14(0.14)	-16.15(0.18)	2.18(0.19)	0.94(0.16)	8.30	dIn	25.0
435	1439+0053	22.96(0.01)	21.73(0.02)	-15.71(0.04)	-16.72(0.06)	1.15(0.02)	0.94(0.02)	8.53	Sd	30.4
437	1440-0008	23.35(0.01)	22.33(0.02)	-14.03(0.05)	-14.95(0.07)	0.96(0.02)	0.85(0.02)	7.92	dIn	20.8
446	1446+0231	23.19(0.01)	22.20(0.02)	-17.08(0.05)	-17.89(0.07)	0.91(0.02)	0.73(0.02)	9.63	Sm	13.4
447	1446+0238	21.47(0.01)	19.89(0.02)	-19.33(0.04)	-20.54(0.06)	1.51(0.02)	1.15(0.02)	9.73	Sc	19.0
462	2303-0006	21.20(0.07)	19.86(0.09)	-20.28(0.09)	-21.21(0.11)	1.27(0.12)	0.86(0.10)	9.71	Sm	27.4
463	2304+0155	21.72(0.06)	20.63(0.07)	-18.63(0.08)	-19.57(0.09)	0.99(0.10)	0.84(0.09)	9.57	SB	27.2
468	2311-000	20.94(0.07)	19.76(0.08)	-18.87(0.09)	-19.80(0.12)	1.10(0.10)	0.86(0.09)	8.95	Sa	16.4
470	2312-0011	20.71(0.06)	18.94(0.07)	-20.33(0.08)	-21.63(0.09)	1.70(0.09)	1.23(0.08)	9.98	Sb	98 11
471	2313+0008	20.92(0.07)	19.57(0.09)	-20.19(0.08)	-21.29(0.12)	1.27(0.12)	1.18(0.10)	9.76	Sb	21.2
473	2315-0000	21.51(0.07)	19.44(0.08)	-19.87(0.09)	-21.24(0.11)	2.00(0.10)	1.47(0.09)	9.71	Sc	24.6
474	2317+0112	20.83(0.06)	19.40(0.07)	-20.19(0.08)	-21.29(0.09)	1.35(0.10)	1.20(0.09)	9.74	Sb	20.2
484	2320+0110	19.57(0.06)	18.60(0.07)	-20.27(0.08)	-21.09(0.09)	0.91(0.09)	0.93(0.08)	9.91	Sb	13.0
485	2320+0107	20.63(0.06)	19.51(0.07)	-19.48(0.08)	-20.46(0.10)	1.05(0.09)	1.09(0.08)	9.84	Sb	11.0
488	2327-0007	22.27(0.06)	20.83(0.07)	-18.52(0.08)	-19.76(0.09)	1.36(0.09)	1.16(0.08)	8.99	Sc	38.8
492	2329+0203	22.04(0.06)	20.92(0.07)	-17.77(0.09)	-18.76(0.10)	1.04(0.09)	0.91(0.08)	8.99	Sc	18.4
515	2349+0248	21.05(0.06)	19.77(0.07)	-19.35(0.08)	-20.27(0.09)	1.20(0.09)	0.85(0.08)	9.79	Sbc	31.2

Notes:

(1) Correlative number to the Impey et al. (1996) catalogue. Bold face identifications denote the 21 face-on galaxies studied in detail in this paper.

(2) Name from the Impey et al. (1996) catalogue.

(3) Surface brightness of the inner 2 kpc diameter in the B band.

(4) Surface brightness of the inner 2 kpc diameter in the R band.

(5) Absolute magnitude in the B band, to the isophote $\mu_B = 25.0$ mag arcsec^{-2}.

(6) Absolute magnitude in the R band, to the isophote $\mu_R = 24.0$ mag arcsec^{-2}.

(7) $B-R$ color in the inner (2 kpc) galaxy region.

(8) Total $B-R$ color.

(9) HI mass in solar masses, taken from Impey et al. (1996).

(10) Hubble type from Impey et al. (1996) catalogue.

(11) Effective diameter (in arcsec), the diameter at which half of the light is included, from Impey et al. (1996).

Table 3: Optical structural parameters for the selected 21 face-on, nucleated spiral galaxies.

	B				R			
No.	$\mu_{0,B}$	$\mu_{0,D}$	h_B	h_D	$\mu_{0,B}$	$\mu_{0,D}$	h_B	h_D
(1)	(2)	(3)	(4)	(5)	(2)	(3)	(4)	(5)
59	18.31	21.89	0.53	10.4	17.04	20.19	0.72	8.45
100	20.62	22.49	0.19	4.27	19.40	21.42	0.19	3.95
196	18.73	21.34	0.56	4.89	17.23	19.99	0.54	4.47
207	19.95	21.63	1.01	6.52	16.81	20.30	0.94	9.85
213	19.56	22.34	0.80	5.96	18.66	21.17	0.91	5.08
224	20.42	22.82	2.18	25.1	18.25	20.90	1.96	18.5
242	18.50	20.98	0.53	3.38	16.85	19.63	0.40	3.07
264	22.05	22.91	0.15	0.34	20.84	22.02	0.14	0.34
324	21.17	21.93	2.58	6.54	19.33	20.58	1.93	5.76
345	19.60	22.55	1.20	11.7	18.56	21.81	1.36	12.6
377	22.09	...	3.60	...	20.72	...	3.01	...
410	20.74	...	1.55	...	19.70	...	1.67	...
447	20.78	21.74	1.24	4.09	19.23	20.54	1.34	4.10
463	20.97	...	1.85	...	19.94	...	1.92	...
468	20.20	...	0.92	...	19.11	...	1.14	...
470	20.09	20.52	1.34	4.04	18.46	19.72	1.44	4.71
471	19.43	20.72	0.57	4.20	18.39	19.67	0.74	4.21
473	19.16	21.42	0.90	4.99	17.73	20.04	0.99	4.70
484	18.40	...	0.70	...	17.58	...	0.79	...
488	21.14	22.65	0.62	5.02	19.67	21.46	0.59	4.95
515	20.18	21.78	0.87	5.50	18.89	20.71	0.87	4.96

(1) ID number correlated with the Impey et al. (1996) catalogue.

(2) Bulge central surface brightness in units of mag arcsec^{-2}.

(3) Disk central surface brightness in units of mag arcsec^{-2}.

(4) Exponential scale length of the bulge in units of kpc.

(5) Exponential scale length of the disk in units of kpc.

Note: Dots indicate that no disk has been detected with a signal to noise ratio larger than 1.5.

Table 4: Near-IR structural parameters for the selected 21 face-on, nucleated spirals selected.

		J						K_s					
No.	*cz*	$\mu_{0,B}$	h_B	$\mu_{0,D}$	h_D	μ_{eff}	r_{eff}	$\mu_{0,B}$	h_B	$\mu_{0,D}$	h_D	μ_{eff}	r_{eff}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(3)	(4)	(5)	(6)	(7)	(8)
59	5028.0	...	...	22.33	40.29	22.33	20.62	...	...	21.21	33.96	21.08	14.55
100	2615.0	...	...	24.74	15.66	28.76	40.38	...	...	24.02	13.88	27.75	24.73
196	11401.0	15.57	0.23	21.70	2.93	...	...	14.90	0.23	20.64	3.07	...	...
207	17324.0	17.80	2.15	22.04	29.68	...	...	16.70	2.16	20.36	17.17	...	...
213	9592.0	14.72	0.31	19.16	3.16	...	...	16.55	0.71	18.77	5.09	...	...
224	29213.0	...	...	18.87	12.60	18.92	3.12	...	...	17.46	10.98	16.37	1.62
242	8825.0	18.43	1.53	20.90	13.27	...	...	17.58	1.60	20.06	13.34	...	...
264	1018.0	...	...	22.36	0.82	...	...	...	...	21.55	0.82	...	...
324	22259.0	22.00	5.40	22.50	22.07	...	...	20.50	7.71	21.70	28.19	...	...
345	23655.0	19.50	6.49	22.62	43.36	...	...	18.72	6.30	21.95	46.28	...	...
377	12040.0	22.56	7.79	23.82	37.69	...	...	22.26	5.68	23.05	36.22	...	...
410	7518.0	22.37	1.92	21.61	10.04	...	...	21.77	1.88	20.96	9.38	...	...
447	10281.0	21.23	2.36	21.14	11.60	...	...	20.44	7.63	22.02	23.46	...	...
463	5244.0	21.78	3.06	22.54	17.22	...	...	21.14	2.53	21.76	17.63	...	...
468	4392.0	21.26	0.65	20.87	7.10	...	...	20.39	1.00	20.29	7.43	...	...
470	15380.0	...	...	22.40	18.53	23.75	28.32	...	...	21.07	5.37	24.11	75.59
471	8667.0	...	...	21.27	12.93	25.41	41.83	...	...	20.46	12.54	24.84	51.72
473	8938.0	...	...	...	...	...	...	...	...	...	...	...	...
484	8951.0	20.18	3.11	20.46	8.70	...	...	19.31	3.03	19.89	9.33	...	...
488	5207.0	21.32	1.68	22.92	18.82	...	...	20.69	1.86	22.34	23.58	...	...
515	5324.0	20.43	3.03	22.04	14.47	...	...	19.65	2.74	21.18	12.56	...	...

(1) ID number correlated with the Impey et al. (1996) catalogue.

(2) Heliocentric velocity, from Impey et al. (1996) catalogue.

(3) Bulge central surface brightness in mag arcsec^{-2}.

(4) Exponential scale length of the bulge in kpc.

(5) Disk central surface brightness in mag arcsec^{-2}.

(6) Exponential scale length of the disk in kpc.

(7) Effective surface brightness in mag arcsec^{-2}.

(8) Effective radius in kpc.